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Fundamentals of Technology Roadmapping

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Abstract

Technology planning is important for many reasons. Globally, companies are facing many competitive problems. Technology roadmapping, a form of technology planning, can help deal with this increasingly competitive environment. While it has been used by some companies and industries, the focus has always been on the technology roadmap as a product, not on the process. This report focuses on formalizing the process so that it can be more broadly and easily used. As a DOE national security laboratory with R&D as a major product, Sandia must do effective technology planning to identify and develop the technologies required to meet its national security mission. Once identified, technology enhancements or new technologies may be developed internally or collaboratively with external partners. For either approach, technology roadmapping, as described in this report, is an effective tool for technology planning and coordination, which fits within a broader set of planning activities. This report, the second in a series on technology roadmapping, develops and documents this technology roadmapping process, which can be used by Sandia, other national labs, universities, and industry. The main benefit of

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technology roadmapping is that it provides information to make better technology investment decisions by identifying critical technologies and technology gaps and identifying ways to leverage R&D investments. It can also be used as a marketing tool. Technology roadmapping is critical when the technology investment decision is not straight forward. This occurs when it is not clear which alternative to pursue, how quickly the technology is needed, or when there is a need to coordinate the development of multiple technologies. The technology roadmapping process consists of three phases — preliminary activity, development of the technology roadmap, and follow-up activity. Preliminary activity includes: (1) Satisfy essential conditions. (2) Provide leadership/sponsorship. (3) Define the scope and boundaries for the technology roadmap. Development of the technology roadmap includes: (1) Identify the "product" that will be the focus of the roadmap. (2) Identify the critical system requirements and their targets. (3) Specify the major technology areas. (4) Specify the technology drivers and their targets. (5) Identify technology alternatives and their time lines. (6) Recommend the technology alternatives that should be pursued. (7) Create the technology roadmap report. Follow-up activity includes: (1) Critique and validate the roadmap. (2) Develop an implementation plan. (3) Review and update.

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Technology planning is important for many reasons. Globally, companies are facing many competitive problems. Technology roadmapping, a form of technology planning, can help deal with this increasingly competitive environment. While it has been used by some companies and industries, the focus has always been on the technology roadmap as a product, not on the process. This report focuses on formalizing the process so that it can be more broadly and easily used.

As a DOE national security laboratory with R&D as a major product, Sandia must do effective technology planning to identify and develop the technologies required to meet its national security mission. Once identified, technology enhancements or new technologies may be developed internally or collaboratively with external partners. For either approach, technology roadmapping, as described in this report, is an effective tool for technology planning and coordination, which fits within a broader set of planning activities. This report, the second in a series on technology roadmapping, develops and documents this technology roadmapping process, which can be used by Sandia, other national labs, universities, and industry.

The main benefit of technology roadmapping is that it provides information to make better technology investment decisions by identifying critical technologies and technology gaps and identifying ways to leverage R&D investments. It can also be used as a marketing tool. Technology roadmapping is critical when the technology investment decision is not straight forward. This occurs when it is not clear which alternative to pursue, how quickly the technology is needed, or when there is a need to coordinate the development of multiple technologies.

The technology roadmapping process consists of three phases — preliminary activity, development of the technology roadmap, and follow-up activity.

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Fundamentals of Technology Roadmapping

Introduction

Technology planning is important for many reasons. Globally, companies are facing many problems. Products are becoming more complicated and customized. Product time to market is shrinking. Product life is shortening. A short-term focus is reducing investment funding. There is increased competition. Cut-backs are occurring because of increased competition. These problems require companies to be more focused and better understand both their industry and markets. Better technology planning can help deal with this increasingly competitive environment. A few U.S. companies and industries are beginning to use technology roadmapping as a technology planning tool to better position themselves and their products.

As a DOE national security laboratory with a strong technology component, Sandia National Laboratories must do effective technology planning to identify and develop the technologies required to meet its mission. Declining budgets make this technology planning even more critical. Sandia must quickly identify and develop critical, mission-relevant technologies, whereas in the past, with greater budgets, a broader range of potentially useful technologies could be considered and explored. Also since reduced budgets make it impossible to independently develop all of the required technologies, technology partnerships can provide a way to leverage these limited resources. Once identified, technology enhancements or new technologies may be developed internally or collaboratively with external partners. For either approach, technology roadmapping, as described in this paper, is an effective technology planning tool to help identify product needs, map them into technology alternatives, and develop project plans to ensure that the required technologies will be available when needed.

Technology roadmapping is an important tool for collaborative technology planning and coordination for corporations as well as for entire industries. It is a specific technique for technology planning, which fits within a more general set of planning activities. As a result of technology roadmapping, a company or an industry can make better investment decisions because it has better information to:

- Identify critical product needs that will drive technology selection and development decisions.
- Determine the technology alternatives that can satisfy critical product needs.
- Select the appropriate technology alternatives.
- Generate and implement a plan to develop and deploy appropriate technology alternatives.

Technology roadmapping is driven by a need, not a solution. For example, if the need exists for an energy efficient vehicle that gets better miles per gallon, then lightweight composite materials is a possible solution. There may be other more appropriate solutions. Therefore, you must start with the need, not a pre-defined solution. It is a fundamentally different approach to start with a solution and look for needs. Technology roadmapping provides a way to identify, evaluate, and select technology alternatives that can be used to satisfy the need. However, this roadmap is only a high-level strategy for developing these technologies. A more detailed plan is then needed to specify the actual projects and activities. This is simply traditional project management, not something unique to technology roadmapping. Unfortunately, all of these activities are sometimes combined under the label of technology roadmapping, which causes much confusion about what the unique characteristics and real benefits of technology roadmapping are.

Different people use the term roadmapping (or even technology roadmapping) to mean different things. To eliminate this confusion, this report clarifies what is meant by both technology roadmapping and a technology roadmap by defining them, identifying uses and benefits of technology roadmapping, and explaining the technology roadmapping process. It also describes the broader planning and business development context within which technology roadmapping is done and the knowledge and skills required by the process. Since this is the second report of an evolving series on this methodology, the final section identifies several issues that are still being addressed and which will probably be the focus of future reports in the series.

Uses and Benefits of Technology Roadmapping

At both the individual corporate and industry levels, technology roadmapping has several potential uses and resulting benefits. Three major uses are:

- First, technology roadmapping can help develop a consensus about a set of needs and the technologies required to satisfy those needs.

- Second, it provides a mechanism to help experts forecast technology developments in targeted areas.

- Third, it can provide a framework to help plan and coordinate technology developments both within a company or an entire industry.

The main benefit of technology roadmapping is that it provides information to help make better technology investment decisions. It does this by:

- First, identifying critical technologies or technology gaps that must be filled to meet product performance targets.

- Second, identifying ways to leverage R&D investments through coordinating research activities either within a single company or among alliance members.

An additional benefit is that as a marketing tool, a technology roadmap can show that a company really understands customer needs and has access to or is developing (either internally or through alliances) the technologies to meet their needs. Industry roadmaps may identify technology requirements that a company can support.

Some companies do technology roadmapping internally as one aspect of their technology planning (corporate technology roadmapping). However, at the industry level, technology roadmapping involves multiple companies, either as a consortium or an entire industry (industry technology roadmapping). By focusing on common needs, companies can more effectively address critical research and collaboratively develop the common technologies. For example, the SIA (Semiconductor Industry Association) Semiconductor Technology Roadmap addressed the requirements for semiconductor manufacturing and the NEMI (National Electronics Manufacturing Initiative) Technology Roadmap addressed the common needs for information products to connect to information networks such as NII (National Information Infrastructure). This level of technology roadmap allows industry to collaboratively develop the key underlying technologies, rather than redundantly funding the same research and underfunding or missing other important technologies. This can result in significant benefits because a certain technology may be too expensive for a single company to support or take too long to develop, given the resources that can be justified. However, combining the resources across companies may make developing the technology possible and consequently the industry more competitive.

What is Technology Roadmapping?

Technology roadmapping is a needs-driven technology planning process to help identify, select, and develop technology alternatives to satisfy a set of product needs. It brings together a team of experts to develop a framework for organizing and presenting the critical technology-planning information to make the appropriate technology investment decisions and to leverage those investments. (For an example of this teaming process at the industry level see Garcia, *Introduction to Technology Roadmapping: The Semiconductor Industry Association's Technology Roadmapping Process*.)

Given a set of needs, the technology roadmapping process provides a way to develop, organize, and present information about the critical system requirements and performance targets that must be satisfied by certain time frames. It also identifies technologies that need to be developed to meet those targets. Finally, it provides the information needed to make trade-offs among different technology alternatives.

Roadmapping can be done at either of two levels — industry or corporate. These levels require different commitments in terms of time, cost, level of effort, and complexity. However, for both levels the resulting roadmaps have the same structure — needs, critical system requirements and targets, technology areas, technology drivers and targets, technology alternatives, recommended alternatives or paths, and a roadmap report — although with different levels of detail. Technology roadmapping within a national laboratory is essentially corporate-level roadmapping, although a national laboratory may participate in an industry roadmapping process.

What is a Technology Roadmap?

A technology roadmap is the document that is generated by the technology roadmapping process. It identifies (for a set of product needs) the critical system requirements, the product and process performance targets, and the technology alternatives and milestones for meeting those targets. In effect, a technology roadmap identifies alternate technology "roads" for meeting certain performance objectives. A single path may be selected and a plan developed. If there is high uncertainty or risk, then multiple paths may be selected and pursued concurrently. The roadmap identifies precise objectives and helps focus resources on the critical technologies that are needed to meet those objectives. This focusing is important because it allows increasingly limited R&D investments to be used more effectively.

Types of Technology Roadmaps

There are different types of technology roadmaps. The product technology roadmap is driven by product/process needs. Since the product technology roadmap is the focus of this report, it is usually referred to simply as a technology roadmap.

Another type of technology roadmap, which is used by some corporations, is an emerging technology roadmap. An emerging technology roadmap differs from a product technology roadmap in two ways:

- First, the emerging technology roadmap lacks the broader product context provided by the product technology roadmap.

- Second, the emerging technology roadmap focuses on (1) forecasting the development and commercialization of a new or emerging technology, (2) the competitive position of a company with respect to that technology, and (3) how the emerging technology and the company's competitive position will develop.

The emerging technology roadmap focuses on a single technology, describes the way it is expected to develop, and may include project plans to support that development. The result of an emerging technology roadmap may be a decision to allocate additional resources to develop the technology and improve your competitive position. The implication is that as the technology develops, uses will be found for it. While this emerging technology roadmap is valuable and has its uses (especially within the context of a product technology roadmap), it is not the type of technology roadmap this report addresses. (For a more detailed discussion of emerging technology roadmaps, see Willyard and McClees, "Motorola's Technology Roadmap Process.")

Still another type of roadmap is the one described by the DOE Environmental Restoration and Waste Management in *Revised Roadmap Methodology Document* (May 1993). This is an example of an issue-oriented roadmap, rather than a technology roadmap, although the availability of a required technology may be considered an issue to be addressed. This roadmapping approach, customized for DOE EM sites, is intended to identify issues and their consequences for project planning and budgeting. This roadmapping process, which is allocated four months in the annual planning and budgeting cycle, feeds the strategic plan, the five year plan, budgeting, and detailed human resource planning.

The uses for this roadmapping approach:

- Communicate planning assumptions and information from the sites to DOE/HQ.
- Support the budgeting process.
- Tie issues to low-level project planning and budgeting documents.

This roadmapping consists of three phases:

1. Assessment (i.e., establish assumption, establish regulatory requirements, establish committed milestones, depict logics and planned activities).
2. Analysis (i.e., identify issues, perform root-cause analysis, and translate issues to activities).
3. Resolution (develop issue-resolution documents and integrate activities with activity data sheets).

Although there are some similarities, this roadmapping approach is fundamentally different (in purpose, scope, and steps) from the technology roadmapping process addressed by this paper.

Planning and Business Development Context for Technology Roadmapping

Technology roadmapping is an iterative process that fits within the broader corporate strategic planning, technology planning, and business development context. However, since there are many successful variations of strategic planning, technology planning, and business development processes, this paper does not address how these are done, only their results.

Planning activities must link three critical elements — customer/market needs, products/services, and technologies. The corporate vision drives the strategic planning effort, which generates high-level business goals and directions. Given a corporate vision, strategic planning involves decisions that identify and link at a high level the customer/market needs a company wants to address and the products and services to satisfy those needs. Given this strategic plan, technology planning involves identifying, selecting, and investing in the technologies to support these product and service requirements. Business development involves planning for and implementing certain aspects of the strategic plan, specifically those involving the development of new products and services and/or new lines of business.

This report addresses technology roadmapping, which is a type of technology planning. However, technology roadmapping is more appropriate in some cases than in others and a decision needs to be made when to use it. Technology roadmapping is critical when the technology investment decision is not straight forward. This occurs when it is not clear which alternative to pursue (e.g., enhance an existing technology or replace it with a new technology), how quickly the technology is needed, or when there is a need to coordinate the development of multiple technologies.

This section has described the context for corporate technology roadmapping. In some cases, a decision is made that the technologies that need to be developed are too expensive or risky for a single corporation to develop independently. If this insight occurs in several companies, there may be a movement toward industry technology road-mapping. In summary, regardless of the level of formality, participation, and resources, there must be a linkage between the technology investment decisions and the business requirements. Technology roadmapping is an effective tool for providing this linkage.

Knowledge and Skills Required for Technology Roadmapping

Both corporate and industry technology roadmapping require a certain set of knowledge and skills. Some of the participants or consultants must know the technology roadmapping process. This includes how to identify needs and technology drivers, as well as how to identify, analyze, and select technology alternatives and paths. Some participants must also have some content knowledge of the area being roadmapped. Different participants may have the content and the technology roadmapping process skills. However, while these skills are important, they are not nearly enough. Equally important are the interpersonal and group process skills.

Therefore, for a corporate- or industry-level roadmapping project, you need a roadmapping consultant and/or facilitator who has both types of skills (roadmapping and interpersonal) or a well-integrated team that includes both types of skills. The road-mapping consultant does not need to be an expert, or even particularly knowledgeable, in the content of the area being roadmapped. In fact, such expertise can be a detriment if the consultant/facilitator becomes too involved in the content of the roadmap. It is not the consultant's roadmap. It should be owned by the group of experts developing the roadmap, so their involvement and commitment is critical.

Technology Roadmapping Process

This section provides an overview of the three phases in the technology roadmapping process (Figure 1). The first phase involves preliminary activity without which the roadmapping probably should not be done. The second phase is the development of the technology roadmap. The third phase is the follow-up and use of the technology roadmap.

Phase I. Preliminary activity

1. Satisfy essential conditions.
2. Provide leadership/sponsorship.
3. Define the scope and boundaries for the technology roadmap.

Phase II. Development of the Technology Roadmap

1. Identify the "product" that will be the focus of the roadmap.
2. Identify the critical system requirements and their targets.
3. Specify the major technology areas.
4. Specify the technology drivers and their targets.
5. Identify technology alternatives and their time lines.
6. Recommend the technology alternatives that should be pursued.
7. Create the technology roadmap report.

Phase III. Follow-up activity

1. Critique and validate the roadmap.
2. Develop an implementation plan.
3. Review and update.

Figure 1. The three phases in the technology roadmapping process.

Phase I: Preliminary Activity

In this phase, the key decision makers must realize/perceive that they have a problem that a technology roadmap can help them solve. They must decide what will be roadmapped and how the technology roadmap will help them make their investment decisions. The acceptance and buy-in of these decision makers is critical to get the resources needed to create the roadmap and the willingness to use it. This process is iterative because as the scope of the roadmap evolves, their buy-in must be maintained. A complication is that different people expect different results and all of them must be at least partly satisfied. The steps in this phase provide some assurance that this essential buy-in will be obtained. However, this buy-in must be maintained throughout the later two phases.

1. Satisfy essential conditions.

For a technology roadmapping effort to succeed, a number of conditions must be satisfied. This step involves checking to ensure that those conditions are already met or that someone is taking the necessary actions to meet them. These required conditions are similar, but not identical, for corporate- and industry-level technology roadmapping:

- There must be a perceived need for a technology roadmap and collaborative development, although a much broader group must perceive this need for an industry roadmap.

- The technology roadmapping effort needs input and participation from several different groups, which bring different perspectives and planning horizons to the process.

- The corporate technology roadmapping process needs participation from various parts of the organization (e.g., marketing, manufacturing, R&D, planning, etc.) as well as from key customers and suppliers.

- The industry technology roadmapping process needs participation from members of the industry, its customers and suppliers, as well as government and universities. The focus should be on areas of common need and adversarial conditions must be avoided.

- The technology roadmapping process should be needs-driven rather than solution-driven. There must be a clear specification of the boundaries of the effort — what is and is not within the scope of the technology roadmap and how will the roadmap be used.

2. Provide leadership/sponsorship.

Because of the time and effort involved in roadmapping, there must be committed leadership/sponsorship. Furthermore, this leadership/sponsorship must come from the group that is going to do the actual implementation and benefit from it. For a corporate-level technology roadmap, this means that the line organization must drive the roadmapping process and use the roadmap to make resource allocation decisions. For an industry level technology roadmap, this means that industry must lead the effort, although its customers and suppliers, along with government and universities, should also be participants in developing, validating, and implementing the technology roadmap.

3. Define the scope and boundaries for the technology roadmap.

This step ensures that the context for the roadmap has been specified. It develops or ensures that a vision exists (for either the industry or corporation) and that a roadmap can support that vision. It identifies why the technology roadmap is needed and how it will be used. Finally, it clearly specifies the scope and boundaries of the roadmap. A roadmap starts with a set of needs. The intended use of the roadmap determines the planning horizon and the level of detail. The time horizon for roadmaps varies, but for industry roadmaps it is typically at least 10 to 15 years, although there are intermediate points every three to five years. Corporate roadmaps may have a shorter time horizon.

This step is important for roadmapping at both the corporate and industry level. However, it is more difficult, complex, and time-consuming at the industry level for two reasons:

- First, there are many levels of needs, which must be decomposed, and different levels of product, subsystems, and/or components that can be roadmapped. The level selected must have a commonality for the various participants.

- Second, since many U.S. companies do not know how to effectively collaborate, this step (and the previous two) involves a major learning effort, so this phase of industry roadmapping can easily take at least six months. The involvement of an industry umbrella organization, such as a consortium or a trade association, can improve the speed and efficiency of the process and can often provide some of the support resources.

Phase II: Development of the Technology Roadmap

This phase involves seven steps. These steps to create the actual technology roadmap are similar for both corporate and industry technology roadmaps, but the resource and time requirements are much greater for an industry roadmap. In both cases, working groups or teams are essential to develop the content of the roadmap.

1. Identify the "product" that will be the focus of the roadmap.

The critical step in roadmapping is to get the participants to identify and agree on common product needs (e.g., for an energy-efficient vehicle) that must be satisfied. This agreement is important to get their buy-in and acceptance of the roadmapping process. Depending on the complexity of the product, there may be many components and levels on which the roadmap may focus. Selecting the appropriate focus is critical.

If there is major uncertainty about the product needs, the use of scenario-based planning can help. For example, for an energy-efficient vehicle there could be a scenario based on a major oil find or a breakthrough in a renewable energy technology that would drastically lower the price of gas or other fuel, or a scenario based on another oil shock that would drastically reduce the supply and drive up the cost. Each scenario must be reasonable, internally consistent, and comparable with the other scenarios in that it affects one or more of the needs postulated for the roadmap. The scenario analysis may/should include extreme cases, but it should not over emphasize them or let them drive the roadmap. The important point is that the scenarios are not ends in themselves. They are only a means for addressing uncertainty in the environment and the needs to improve the quality of the roadmap.

The scenarios are used to better identify the needs, services, or products. In many cases, there will be common needs that apply across all of the scenarios, although the demand may be different for different scenarios. In other cases, a need may be critical for a particular scenario that has too high a probability to be ignored. Some of the work on this type of need could be considered insurance. Over time, as the degree of uncertainty about needs changes, the emphasis on technologies addressing this need could be increased or decreased. This is one of the reasons for periodic reviews and updates of the roadmap and its implementation plan.

2. Identify the critical system requirements and their targets.

The critical system requirements provide the overall framework for the roadmap and are the high-level dimensions to which the technologies relate. Once the participants have decided what needs to be roadmapped (which is not a trivial process), they must identify the critical system requirements. Examples of critical system requirements for an energy-efficient vehicle include mpg, reliability, safety, and cost. Examples of targets include 60 miles per gallon (mpg) by 2000 and 80 mpg by 2005.

3. Specify the major technology areas.

These are the major technology areas that can help achieve the critical system requirements for the product. Examples of technology areas to meet the performance target of 80 mpg by 2005 for an energy efficient car include materials, engine controls, sensors, and modeling and simulation.

4. Specify the technology drivers and their targets.

At this point, the critical system requirements are transformed into technology-oriented drivers for the specific technology areas. These technology drivers are the critical variables that will determine which technology alternatives are selected. For the materials technology area, examples of technology drivers could include vehicle weight and acceptable engine temperature, while for the engine controls technology area a technology driver could be the cycle time for the computer controlling the engine.

Technology drivers are dependent on the technology areas being considered, but they relate to how the technology addresses the critical system requirements. At this point, technology driver targets are also set based on the critical system requirement targets. The technology driver targets specify how well a viable technology alternative must be able to perform by a certain date. For example, to get 80 mpg by 2005 (a system requirement), engine control technology may need to be able to deal with x number of variables and adjust engine parameters every y milliseconds, which requires a processor cycle time of z (e.g., technology driver targets).

5. Identify technology alternatives and their time lines.

Once the technology drivers and their targets are specified, the technology alternatives that can satisfy those targets must be identified. A difficult target may require breakthroughs in several technologies or a technology may impact multiple targets. For each of the identified technology alternatives, the roadmap must also estimate a time line for how it will mature with respect to the technology driver targets. When multiple technologies are being pursued in parallel, decision points need to be identified for when a technology will be considered the winner or when it will be dropped from further consideration.

6. Recommend the technology alternatives that should be pursued.

This step selects the subset of technology alternatives to be pursued. These technology alternatives vary in terms of cost, schedule, and/or performance. One path may get you there faster, another path may be cheaper, while still another path may result in a 20 percent performance improvement over the target. Considering the trade-offs, a faster path may not matter if the technology is not on the critical path for the end product/service. However, if it is on the critical path, then a faster path can result in faster time to market — an important competitive advantage. In some cases, a 20 percent improvement over the minimum performance target may be worth the extra time or cost, while in other cases doubling the performance may not significantly affect the value of the end product if other factors become the dominant constraints. This emphasizes the difference between simply improving performance with respect to a technology metric versus the actual change in the product metrics, which a technology change causes.

To further complicate the problem, a certain technology may help you meet the first one or two targets for a driver but cannot satisfy later targets, while another technology may not satisfy the immediate targets but can meet the subsequent targets. The latter is called a disruptive technology. A disruptive technology is one that cannot satisfy current needs, so it is often ignored in favor of the current technology. However, its potential performance and rate of improvement if it is developed is much greater than the current technology, which it will eventually replace. Without the broader perspective provided by a technology roadmap (or other tools), the disruptive technology is often underfunded or completely ignored. (For more information on disruptive technologies see Bower and Christensen, “Disruptive Technologies: Catching the Wave.”)

In some cases, there may be analytical and modeling tools to help determine which technology alternative to pursue and when to shift to a different technology (i.e., jump to a new technology curve with a disruptive technology). In other cases, the trade-offs and decisions are determined by the best judgment of the experts. In either case, the road-mapping process has consolidated the best information and develop a consensus from many experts. Furthermore, the roadmapping process (at either the corporate or the industry level) has begun a collaborative effort that, when carried into the implementation, will result in more effective and efficient use of limited technology investment resources.

7. Create the technology roadmap report.

By this point you have developed your roadmap(s). It becomes one of the documents within the roadmap report. This report should also include:

- The identification and description of each technology area and its current status.
- Critical factors (show-stoppers) which if not met will cause the roadmap to fail.
- Areas not addressed in the roadmap.
- Technical recommendations.
- Implementation recommendations.

The report may also include additional information. For example, the SIA roadmap report included information on competencies that cut across multiple technologies and political/economic issues that impact the entire U.S. R&D establishment.

Phase III: Follow-up Activity

With early buy-in and support in Phase I, the follow-up activities will be much easier. Without this buy-in, the technology roadmap may not address the issues that the key decision makers need to resolve. As a consequence, the roadmap may not be used. Since relatively few people were involved in developing and drafting the technology roadmap, it must now be critiqued, validated, and accepted by a much larger group that will be involved in any implementation. An implementation plan needs to be developed using the information generated by the technology roadmapping process to make and implement the appropriate investment decisions. Finally, since both the needs and the technologies are evolving, the roadmap needs to be periodically reviewed and updated.

1. Critique and validate the technology roadmap.

In Phase II, a relatively small group or groups of experts and technologists developed a draft technology roadmap or roadmaps if multiple technology areas are involved. This work must be exposed to a much larger group for validation and buy-in for two reasons:

- First, the draft needs to be reviewed, critiqued, and validated. If the recommended technology alternatives are developed, will the targets be met? Are the technology alternatives reasonable? Are any important technologies missed? Is the roadmap clear and understandable to people who were not involved in the drafting process?

- Second, there must be buy-in from the broader corporate or industry group that will be involved in implementing the plan. With an industry roadmap, a large, highly structured workshop is often used to provide this feedback. Implicit in this step is the possible revision of the roadmap.

2. Develop an implementation plan.

At this point, there is enough information to make better technology selection and investment decisions. Based on the recommended technology alternatives, a plan is then developed. At the corporate level, the implementation plan may be one or more project plans, which would be developed based on the selected technology alternatives. At the industry level, the same type of project plan may be developed by the participants, but there is also a need for explicit coordination, which is often done through an industry association. In other cases, there may not be an industry plan — only corporate project plans by the participants.

3. Review and update.

Technology roadmaps and plans should be routinely reviewed and updated. A formal iterative process occurs during this review and update. With the initial roadmap, uncertainty increases with the time frame. Over time, as certain technologies are explored and better understood, some of this uncertainty is reduced, although other areas of uncertainty may develop. Also if scenarios were used up front to address uncertainty about the needs, there may be refinement, or even elimination, of some of the scenarios, which could affect the roadmap or its implementation plan. The review and update cycle allows both the roadmap and the implementation plan to be adjusted for these changes. The review cycle may be based on a company's normal planning cycle or based more appropriately on the rate at which the technology is changing.

Technology Roadmap Example

This section provides an example of a needs-driven technology roadmap and Phase II of the process to develop it. The SIA roadmap, which has become one of the most frequently referenced examples of an industry technology roadmap, is used. The purpose of this example is to show the process flow from product need to actual roadmap, not to completely describe the SIA process and roadmap.

First, the product focus of the roadmap was semiconductors, which could be used in various types of products (such as memories, consumer products, portable computers, and high-performance computers), each of which had different requirements. However, semiconductor manufacturing technology was the common area on which the industry could cooperate. They competed on semiconductor designs and the products that used them, not the underlying manufacturing technology.

Second, the critical system requirements included smaller size (i.e., feature size), lower cost, and power dissipation for portable equipment. As an example of targets, they projected feature size between 1992 and 2007 as declining in three year increments from .5 to .1 microns.

Third, the roadmap identified 11 technical areas (e.g., chip design and test, lithography, and manufacturing systems). Using the critical system requirements as an overall framework, teams were set up for each technical area and technology roadmaps were developed for each area.

Fourth, each team developed a set of technology drivers specific to their area, which were derived from and related to one or more of the critical system requirements. For example, technology drivers in the lithography area that related to feature size included overlay, resolution, and device size. The lithography area was further decomposed into exposure technology; mask writing, inspection, repair, processing, and metrology; and resist, track, and metrology.

Fifth, for each technology area (e.g., lithography) and/or subarea (e.g., exposure technology), the roadmap identified technology alternatives such as x-ray, e-beam, and ion projection. Technology driver performance was projected for each technology alternative for various time points.

Sixth, based on these projections and their impact on the critical system requirement targets, certain alternatives were recommended.

Seventh, the completed technology roadmap report was created in preparation for the follow-up activity. A major workshop was held to critique and validate the roadmap.

The roadmap is being used by Sematech to evaluate and prioritize potential projects. Does the project fit within the roadmap and if so, where? It has also been used by Sandia National Laboratories to determine where its expertise can best be used and to develop projects that address specific parts of the roadmap. Other Sematech participants can also use the roadmap to focus their research and development activities. The roadmap has already undergone two review and revision cycles. The current version [7] is now noticeably different from the initial version.

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Conclusions

Technology roadmapping is a useful technology planning tool in an increasingly competitive environment, such as that faced by Sandia and other national laboratories. For a successful technology roadmapping process, it is critical to identify why you are doing the roadmapping and how it will be used. Technology roadmapping is particularly useful for coordinating the development of multiple technologies, especially across multiple projects. This coordination is critical when dealing with technologies that are related to a corporation's core competencies. The information about and analysis of needs and technology alternatives is far more important than following a precise process and format. In summary, technology roadmapping is a valuable process if done for the right reasons, but it should not be undertaken lightly or without good justification.

Future Work

This report has described the current state of continuing work on technology roadmapping. Future consulting and use of this technology roadmapping methodology will help refine the process and broaden its applicability. Work with consultants and academics will both support these developments and increase the pool of experts in its use. As work continues, future reports will provide updates on its progress. This work will address three areas, with specific needs and funding determining which areas will be developed and how quickly the work will be done.

- The first area involves generic technology roadmapping frameworks and methods. Work in this area is applicable to both corporate and industry roadmapping and to roadmapping within a national laboratory setting. This work will include issues such as implementation, the integration of roadmaps that were developed independently, emerging technology, the application of scenario-based planning to roadmapping, and in the long-term the application of technology roadmapping methods to non-technology or policy-oriented roadmapping.

- The second area focuses specifically on the application of technology roadmapping in a laboratory environment. For example, specifically how does technology road-mapping feed the investment process and help identify and support emerging technologies? What formats and training are needed to provide enough commonality across roadmaps so that they can be related and if necessary integrated? What is the role of the national laboratories in industry roadmapping?

- A third area involves the development of more detailed guidelines and procedures for developing industry roadmaps, which usually involve alliance building and major external workshops rather than just small internal corporate meetings. Some of this work has already been done, but more work is required.

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Roadmapping Glossary

Alternate technology — An alternate technology is one of several technologies that exist or can be developed within the time frame required to meet one or more targets for a technology roadmap. In some cases, two technologies are pure alternatives in that the target can be reached using either technology X or Y. In other cases, they may be complementary, in that X and Y together may allow a target to be obtained.

Corporate Technology Roadmap — This is a technology roadmap developed internally by a single company/university/laboratory as part of their technology planning. This may be done within the context of a broader industry roadmap or it may be done independently of any external planning.

Corporate Technology Roadmapping — This is the technology roadmapping process pursued by an individual company/university/laboratory from which a roadmap or set of roadmaps results.

Critical System Requirement — A CSR is an essential product characteristic. It is derived from product needs by assessing customer requirements, product technologies, and process technologies that are essential in delivering the product in the future.

Disruptive Technology — A disruptive technology is one that falls short of satisfying one or more current customer requirements, but which has such a rapid projected improvement that it will soon overcome this problem. In most cases the disruptive technology overtakes the existing sustaining technology and replaces it. For further information, see the Bower and Christensen reference.

DOE — Department of Energy; a cabinet-level department in the Federal Government.

Emerging Technology — An emerging technology is a new, potentially promising technology perhaps demonstrated in the lab, but not developed enough to clearly identify all of its uses and benefits. Investments in emerging technologies tend to be more positioning than ROI (return-on-investment) decisions. An emerging technology may appear in either a product technology roadmap or an emerging technology roadmap.

Emerging Technology Roadmap (ETRM) — An ETRM is a different type of technology roadmap that maps out the time line and expected performance for a specific technology. As opposed to the type of technology roadmap considered in this paper, an ETRM is not driven by specific product requirements. Often an ETRM is developed by a company and includes estimates of the company's position with the technology relative to potential competitors. For more information about this type of technology roadmap, see the reference to Willyard and McClees.

Industry Technology Roadmap — This is a technology roadmap developed collaboratively to address specific needs of multiple companies, either as a consortium or as an entire industry.

Issues-oriented Roadmap — A roadmap intended to identify issues and their consequences.

Metrics — A metric is a variable that can be quantified and may be used to define a target for either the product or the technology.

National Electronics Manufacturing Initiative (NEMI) — An initiative created by the Electronics Subcommittee under the Civilian Industrial Technology Committee of the National Science and Technology Council. Its purpose is to promote collaborative development by industry, government, and academia of the underlying technology and infrastructure required to facilitate manufacture of new high-technology electronic products in the U.S.

Milestone — Milestones reflect the technology progress along a time line necessary for achieving the performance targets.

Product — Product in the context of this paper refers to a product, a service, or a process.

Product Needs — Products that customers have identified they need or that technologists believe they can produce as a result of their technologies. Product needs are derived by merging both market pull and technology push. Products involve the application of technologies to solve problems of customers. Roadmaps also depend on the technologist's forecast of product capabilities that our customers may not be aware of. In some cases a roadmap addresses a need for which there is no current product.

Product Technology Roadmap (PTRM) — This is the type of technology roadmap considered in this paper (as opposed to an emerging technology roadmap). Referred to in this paper as simply a technology roadmap, this type of technology roadmap is driven by a set of product needs, which have been refined to a set of specific targets.

Roadmap — This is a generic term that many people use as a synonym for a plan of any type. In this paper, this term without one or more modifiers is avoided because of the confusion about its meaning. In the generic sense the authors refer to a plan, not a roadmap. Technology roadmap is the term for the type of plan developed using the methodology described in this paper. In some cases, to avoid confusion an additional modifier (product or emerging) may be used.

Scenario-based Planning — This is a planning methodology that explicitly addresses uncertainty about the future. This methodology allows planners to explicitly identify several alternate future states or scenarios. One can then consider prerequisites for or consequences of each alternative. In the technology roadmapping context, this approach provides a mechanism to deal with uncertainty in either product needs or technological developments.

Semiconductor Industry Association (SIA) — The industry association that managed the development of the SIA roadmap development. SIA was created in 1977 when U.S. industry banded together to address competitiveness issues in world markets.

Strategic Business Development (SBD) — SBD is planning for, and implementation of, certain aspects of the strategic plan, specifically those involving the development of new products and services and/or new lines of business.

Strategic Planning — Strategic planning is the generation of high-level business goals and directions for the company; given a corporate vision, it involves decisions that identify and link at a high level the customer/market needs a company wants to address and the products and services to satisfy those needs.

Target — A target is the quantitative value that the technology driver must achieve by a certain date.

Technology — Technology is a use of science- and engineering-based knowledge to meet a need.

Technology Driver — The technology drivers are the critical variables that determine which technology alternatives will be pursued. They are dependent on the technology areas, but relate to how the technology addresses the critical system requirements.

Technology Planning — Technology planning is the process for identifying, selecting, and investing in the technologies that are required to support those product and service requirements identified in a company's strategic plan. Technology roadmapping is only one of many forms of technology planning.

Technology Roadmap — A technology roadmap is the output of the technology roadmapping process at either the corporate or the industry level. It identified (for a set of product needs) the critical system requirements, the product and process performance targets, and the technology alternatives and milestones for meeting those targets.

Technology Roadmapping — Technology roadmapping is a needs-driven technology planning process to help identify, select, and develop technology alternatives to satisfy a set of product needs.

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